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THE INFLUENCE OF BLAST HOLES STEMMING ON THE BREAKING YIELD OF ROCKS FRAGMENTED WITH EXPLOSIVES

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Abstract: *Stemming of blast holes is an essential operation for controlled explosions, serving the purpose of filling the voids left after loading with explosives. This process prevents the escape of gases produced during the explosion, which have a pressure of around 10,000 daN/cm², and enhances the breaking effect while reducing dust and noise. Efficient use of stemming can significantly reduce the consumption of explosives and, consequently, the costs of rock fragmentation through drilling and blasting operations, allowing a reduction in explosive consumption by 20-25%. Furthermore, improper stemming of blast holes results in low breaking efficiency, large material granulation, misfires, and, in other words, increased costs for drilling, blasting, and crushing operations, as well as potential accident hazards due to misfires. In this article, we will explore the materials used for stemming, the technologies employed, and improvement proposals to maximize the efficiency and safety of mining operations, leading to more efficient and safer use of explosives in rock fragmentation operations, enhancing breaking efficiency while reducing associated costs and risks.*
Keywords: *civil explosives, stemming, drill-blast works, firing parameters, burst yield, controlled explosions*

1. Introduction

The density of geological exploration drill holes is one of the primary bases for designing the loading structure of blast holes. The development of the mining industry is deeply interconnected with sustainability principles, and improving blasting efficiency is an essential factor in implementing sustainable mining practices. With the continuous increase in global demand for minerals, mining companies must not only boost production but also pay close attention to environmental sustainability. This entails rational control of vibrations and noise during operations to minimize negative environmental impacts. Nevertheless, the current efficiency of using explosives in rock fragmentation remains relatively low, with a significant portion of the explosion energy dissipating as vibrations or air shocks [1-4].

Therefore, there is an urgent need to improve the energy efficiency of explosives used in rock fragmentation and to mitigate secondary negative effects, thereby facilitating the sustainable development of the mining industry. Burdening plays a crucial role in optimizing the use of explosive energy. [5-8].

The length of the blast hole is a particularly important parameter in blast design, and its rational application to enhance the utilization of explosion energy has been demonstrated in various studies. [9-12].

During the propagation of detonation waves from the explosive charge to the stemming material, differences in properties between the explosion products (high-pressure and high-temperature gases) and the stemming material can influence the propagation of shock and stress waves, as well as the ejection of gas and stemming. Thus, investigating stemming materials becomes essential. Multiple research efforts have explored alternative stemming materials to improve rock fragmentation and reduce the generation of fly rock. These alternatives include gypsum stems, rubber-assisted stems (rubber plugs), crushed aggregates, and angular aggregates. Although these materials have shown potential benefits, they are often less common, can be relatively costly, and may have limited availability regarding raw material source [13-16].

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In comparison, clay and sand have the advantage of being widely available. Additionally, their use in underground mining provides multiple benefits, including ease of transport, lower costs, and non-toxicity. Water, a common substance, helps reduce explosive dust and can prevent the clogging of blast holes after blasting in deep holes. However, research on the use of clay, sand, or water as stemming materials is still incomplete and requires further investigation.

According to occupational safety regulations in the mining industry of Romania, specific requirements for stemming blast holes are as follow:

- short holes (0.4-0.6 m): must be stemmed at least 0.3 m;
- medium holes (up to 1.5 m): must be stemmed at least half their length;
- long holes (longer than 3 m): must be stemmed one-third of their length [17,18].

Blasting unstammed holes is prohibited, and the length of stemming is determined by the blasting order in day-to-day mining operations.

2. Methodological considerations on the mechanics of explosion and the role of stemming material

The stemming material plays a crucial role in confining the gases produced by the explosion within the blast hole, thereby increasing the pressure and ensuring efficient rock fragmentation. The efficiency of this process depends on the density and compressibility of the stemming material (Equation 1).

$$P_{explosion} = \frac{F_{gases}}{A} \quad (1)$$

where:
$P_{explosion}$ – explosion pressure,
F_{gases} – force exerted by the produced gases,
A – area of the stemmed surface.

Stemming materials vary in their ability to absorb and disperse the energy produced by the explosion. An inadequate stemming material may allow gas escape and reduce the detonation efficiency (Equation 2).

$$E_{absobed} = \frac{1}{2} \cdot m_{stemming} \cdot v_{gases}^2 \quad (2)$$

where:
$E_{absorbed}$ – energy absorbed by the stemming material,
$m_{stemming}$ – mass of the stemming material,
v_{gases} – velocity of the gases produced by the explosion.

2.1. The influence of stemming on blasting parameters

In the process of rock fragmentation through controlled explosions, blasting parameters are essential to ensure the efficiency and safety of blasting operations. These parameters include the charge diameter (influences the breaking energy and shock wave propagation); charge length (determines the distribution of explosive energy along the blast hole); stemming (prevents the escape of explosive gases, enhancing the breaking effect and reducing dust and noise); the distance between the explosive and the blast hole wall—coupling (affects how energy is transferred to the rock); initiation type and initiation point (determines the detonation method and shock wave propagation).

Stemming has a major influence on improving the quality of blasting operations because it favours:

a. Increasing gas pressure - Stemming prevents the escape of gases produced by the explosion, which increases internal pressure and, consequently, the efficiency of rock fragmentation. Gas pressure can reach values of around 10,000 daN/cm², leading to efficient material displacement.

b. Uniform energy distribution - The inert material used in stemming ensures uniform distribution of explosive energy, preventing local stress concentrations that could lead to uncontrolled fractures. This contributes to more controlled and efficient rock fragmentation.

c. Reduction of dust and noise - Stemming reduces the release of dust and noise, improving working conditions and reducing environmental impact. More complete combustion of the explosive due to effective stemming leads to reduced emission of toxic gases.

d. Economy of explosives - Proper stemming can reduce the required amount of explosives by 20-25%, resulting in significant operational cost savings. Increased explosion efficiency allows for the use of smaller quantities of explosives to achieve the same breaking effect.

e. Control of explosion direction - By controlling how explosive energy is released and distributed, stemming allows for more precise direction of shock waves. This is essential for executing a blasting plan that minimizes the risk of damage to adjacent structures or equipment.

Stemming offers numerous advantages including: increased efficiency of explosives; enhanced safety by reducing the risk of accidental or incomplete detonations; cost reduction through more efficient use of explosives; the decrease of dust and noise during detonation.

Despite its advantages, stemming also has certain disadvantages: namely the need for specialized, expensive equipment that requires regular maintenance; dependence on the experience and qualifications of the operator handling the equipment during stemming operations; and the potential negative environmental impact of the stemming and detonation process.

2.2. Physicochemical phenomena that may occur during stemming and influence the explosion power in blast holes

The most important physicochemical phenomena that may occur during the stemming operations of blast holes are:

a. Friction and heating - Friction between the stemming material and the walls of the hole can generate heat. This can influence the chemical stability of explosives and may lead to premature reactions if the temperature becomes sufficiently high.

b. Uncontrolled chemical reactions - Chemical reactions between the stemming material and the explosive or between the stemming material and the walls of the hole can affect the stability of the explosion. Certain materials may catalyse undesirable reactions or react with the explosives, leading to reduced efficiency or even safety risks.

c. Moisture absorption - The absorption of moisture by stemming materials can affect the physical and chemical properties of explosives. Hygroscopic materials, such as certain clays, can absorb water and thus alter the chemical composition and reactivity of the explosives.

d. Thermal conductivity - The thermal conductivity of the stemming material influences how heat is dissipated during detonation. Materials with high thermal conductivity can disperse heat more rapidly, which can affect the local temperature and the efficiency of the detonation.

e. Pressure and compaction - The pressure exerted by the stemming material on the explosive can affect the detonation velocity and explosion power. An overly compressible or insufficiently compacted stemming material can allow the escape of explosive gases, thereby reducing the efficiency of the detonation.

f. Change of material state - Phase changes of the stemming material (e.g., from solid to liquid) can influence the behaviour of the explosion. If a stemming material melts at high temperatures, it can affect the distribution of explosive force.

g. Ionization and plasma generation - In the case of very intense explosions, the ionization of the stemming material or the explosive itself can create plasma, which can alter the dynamics of the explosion and its effect on the surrounding rock.

h. Gases produced by chemical reactions - Gases produced by chemical reactions of the explosives and the stemming material influence the internal pressure and the efficiency of rock fragmentation. The chemical composition of the gases and the rate at which they expand are crucial for the final effect of the explosion.

i. Catalyst effect - Certain stemming materials can act as catalysts, accelerating or altering the chemical reactions of the explosives. This can affect the detonation velocity and the total energy released.

j. Gas desorption - The desorption of gases adsorbed on the surface of the stemming material can influence the pressure and temperature within the blast hole during detonation. Porous materials can retain and release gases, thus modifying the dynamics of the explosion.

3. Materials used for stemming blast holes

The materials used for stemming blast holes are diverse and have specific characteristics that make them suitable for different mining applications. Among these materials are:

- Inert dust, resulting from rock grinding, is used for stemming holes with both high and low inclinations, with filling done either gravitationally or mechanically;
- Detritus, consisting of rock fragments from drilling, is primarily used for stemming drill holes with high inclinations;
- Sand is used due to its fine granulation and controlled moisture content, making it suitable for air-compressed stemming. It has granules up to 4 mm and a moisture content of 4÷5%;
- Clay can be used alone or mixed with sand, ensuring the sealing and stability of the stemming;
- Sand-clay mix is a combination used to improve the quality of the stemming;

- Cement mortar cartridges are prefabricated from a mixture of cement and sand (1:6), offering high compressive strength;
- Plastic plugs are used to seal and stabilize the stemming;
- Water is used in downward-inclined holes, often in polyethylene vials or other plastic containers.

The materials that can be used for stemming boreholes in mining, along with their characteristics and specific uses, are presented in the following table:

Table 1. Materials used for stemming

Material	Specific Use	Characteristics
Inert Dust	High and low inclination holes	Fine granulation, gravitational or mechanical filling
Debris	High inclination drill holes	Free-falling rock fragments
Sand	Air-compressed holes, all mines	Granules < 4 mm, 4-5% moisture
Clay	Sealing and stability	Used alone or mixed with sand
Sand-Clay Mix	Improving stemming quality	Combination for sealing and stability
Cement Cartridges	Prefabricated, high inclination holes	Cement/sand mix (1:6), compressive strength
Plastic Plugs	Sealing and stabilizing	Various diameters
Water	Downward-inclined holes, water-resistant explosives	Polyethylene vials or direct pouring

Debris and inert dust are particularly used for stemming high inclination drill holes, with filling achieved through the free fall of the material into sections not filled with explosives. Inert dust and sand are used for both high and low inclination drill holes, with mechanical filling done using a compressed air gun.

Stemming with clay involves preparing clay cartridges that are inserted into the holes using a stemming rod. The quality of the stemming can be improved by mixing clay with sand in a 3:1 ratio, reducing the consumption of explosives by 10-15% and increasing the fragmentation coefficient of the holes.

Cement mortar cartridges are made from a mixture of cement and sand in a 1:6 ratio, offering a compressive strength of about 11 daN/cm². Stemming is done by inserting a clay cartridge following the explosive, followed by cement cartridges, with the last cartridge being clay to ensure sealing.

Water stemming is suitable for downward-inclined holes, where water is poured over the explosives until the hole is filled. This method is effective only when using water-resistant explosives. Water stemming can also be achieved using polyethylene vials, which are inserted into the holes and filled with water. For these vials, the last cartridge in the stemmed hole is clay to ensure sealing.

4. Proposals for improving stemming

Stemming plays an essential role in maintaining explosion gas pressure within the mine hole and reducing noise. Improper stemming can lead to suboptimal outcomes such as low fragmentation efficiency, large particle sizes of resulting material, and misfires in the work front.

Explosive materials constitute a significant portion of mining operational costs, making their conservation crucial. Efficient stemming can considerably reduce explosive consumption and thus operational costs.

Given that drilling, like the explosives themselves or initiation materials, plays a well-defined role in achieving maximum explosive utilization efficiency, the following proposals can be considered to enhance stemming practices:

- there is a need for a well-defined and standardized technological regime for stemming, applicable across all Ministry of Mines units;

- centralizing stemming production in a specialized mining unit capable of manufacturing and delivering the required stemming materials to mining operations. This unit should be equipped with machinery for producing stemming materials from a mixture of clay and sand at a predetermined moisture level, in the form of cartridges of various diameters and lengths;
- proper packaging of stemming materials to maintain constant moisture content for an extended period is crucial. Such stemming materials should be distributed to work fronts alongside explosives based on precise calculations performed by technical personnel;
- implementing a technological regime for the production and use of stemming materials that educates the entire mining workforce about its role and importance, leading to positive outcomes in terms of efficiency and safety of explosions.

Implementing these proposals would lead to more efficient and safer use of explosives in mining operations, improving fragmentation efficiency and reducing associated costs and risks. Therefore, stemming should be recognized for its importance and treated as an essential aspect of controlled explosions.

4.1. Methodology for optimizing stemming materials

To select the optimal stemming material, a rigorous evaluation of several criteria is necessary:

a. Density and compressibility

Density (ρ) and compressibility (Cc) are critical for ensuring proper confinement of explosion gases. Stemming materials with high density and optimal compressibility retain the produced gases, thereby increasing internal pressure (Equations 3 and 4).

$$\rho = \frac{m}{V} \tag{3}$$

$$C_c = \frac{\Delta V}{V_o} = \frac{V_o - V_f}{V_0} \tag{4}$$

where:
m – material mass,
V – the volume of the material,
V_0 – initial volume,
V_f – final volume.

b. Coefficient of friction

The coefficient of friction (μ) measures the resistance of the stemming material against the walls of the mine hole. A suitable coefficient of friction prevents gas leakage and maintains the necessary pressure for efficient fragmentation (Equation 5).

$$F_f = \mu \cdot N \tag{5}$$

where:
F_f – friction force,
N – the normal force exerted on the stemming material.

c. Chemical and mechanical stability

The stability of stemming material is crucial to prevent undesirable chemical reactions and disintegration during explosions. This is quantified by chemical stability factor (S_c) and mechanical stability factor (S_m) (Equation 6).

$$S_{total} = S_c \cdot S_m \tag{6}$$

where:
S_c – chemical stability factor,
S_m – the mechanical stability factor.

d. Environmental and health impact

The impact of stemming materials on the environment and health is assessed by the amount and toxicity of the produced dust (Equation 7).

$$I = \frac{M_{dust}}{M_{Total}} \tag{7}$$

where:
I – the impact,
M_{dust} – mass of dust produced,
M_{Total} – mass of dust produced.

e. Costs
Costs are evaluated based on the unit price of stemming material (Equation 8).

$$C = P \cdot M \tag{8}$$

where:
C – the total cost,
P – price per mass unit,
m – mass of the material.

Calculating the total score
The total score for each stemming material is computed as a weighted sum of scores obtained for each criterion (Equation 9):

$$S_{Total} = w_1 \cdot \left(\frac{\rho}{\rho_{\max}}\right) + w_2 \cdot \left(\frac{C_{cmax} - C_c}{C_{cmax} - C_{cmin}}\right) + w_3 \cdot \left(\frac{\mu}{\mu_{\max}}\right) + w_4 \cdot \left(\frac{S_{total}}{S_{total,max}}\right) + w_5 \cdot \left(\frac{I_{min}}{I}\right) + w_6 \cdot \left(\frac{C_{min}}{C}\right) \tag{9}$$

where:
$w_1, w_2, w_3, w_4, w_5, w_6$ – the weights of each criterion
ρ_{max}, C_{cmax}, C_{cmin}, μ_{max}, $S_{total,max}$, I_{min}, C_{min} – reference values for normalization

Table 2. Evaluation table

Criterion	Sand	Clay	Cement Mortar	Gravel	Water (Ampoules)
ρ (g/cm³)	1.6	2.0	2.4	2.2	1.0
C_c	0.15	0.25	0.20	0.10	0.05
M	0.6	0.5	0.7	0.6	0.1
S_{total}	0.8	0.9	0.95	0.85	0.99
I	0.05	0.03	0.02	0.04	0.01
C (Euro/kg)	5	6	8	4	10

Equal weights assumption: w1=w2=w3=w4=w5=w6=1.
Reference values for normalization: $\rho_{max} = 2.4$; $C_{cmax} = 0.25$; $C_{cmin} = 0.05$; $\mu_{max} = 0.7$; $S_{total,max} = 0.99$; $I_{min} = 0.01$; $C_{min} = 4$.

4.2. Assessment of the Impact of stemming materials on explosive efficiency

To assess the efficiency of stemming materials used in blasting operations aimed at increasing rock fragmentation with explosives, the following calculations can be performed:

a. Internal pressure and fragmentation

Stemming materials influence the internal pressure within the blast hole, thereby affecting rock fragmentation. Optimal internal pressure is achieved when the stemming material retains the gases produced long enough to ensure complete fragmentation (Equation 10).

$$P_{intern} = P_{initial} \cdot e^{-\alpha t} \tag{10}$$

where:
P_{intern} - internal pressure in the blast hole,
$P_{initial}$ - initial explosion pressure,

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α - attenuation coefficient,
t – time.

b. Detonation velocity and explosive efficiency

Explosives have a specific detonation velocity that determines their efficiency. Stemming materials that provide optimal confinement enable explosives to achieve their maximum detonation velocity (Equation 11).

$$v_{detonation} = \sqrt{\frac{2 \cdot E}{m}} \tag{11}$$

where:
$v_{detonation}$ - detonation velocity,
E - energy released by the explosive,
m - mass of the explosive.

Let's consider an example with ANFO (Ammonium Nitrate Fuel Oil) as the explosive and compare the effect of different drilling materials on detonation efficiency.

- Parameters for ANFO explosive:
  ρ = 0.85 g/cm³; $v_{detonation}$ = 3200 m/s; E = 3.9 MJ/kg.
- Drilling materials and parameters:
  - Sand: ρ = 1.6 g/cm³, μ = 0.6;
  - Clay: ρ = 2.0 g/cm³, μ = 0.5;
  - Cement Mortar: ρ = 2.4 g/cm³, μ = 0.7.
- Attenuation coefficients: α_{sand} = 0.1; α_{clay} = 0.08; $\alpha_{cemen\ t}$= 0.06
- $P_{initial}$ = 1000 kPa; t = 0.01 s.

The internal pressure created by the explosive considering the stemming materials can be calculated as follows (Equations 12):

$$\begin{aligned} P_{internal,\ sand} &= P_{initial} \cdot e^{-\alpha_{sand} \cdot t} \approx 990kPa \\ P_{internal,\ clay} &= P_{initial} \cdot e^{-\alpha_{clay} \cdot t} \approx 992kPa \\ P_{internal,\ cement} &= P_{initial} \cdot e^{-\alpha_{cement} \cdot t} \approx 994kPa \end{aligned} \tag{12}$$

In this example, stemming materials significantly affect internal pressure and detonation efficiency.

4.3. Case study: Evaluation of stemming materials for civilian explosives

The optimal stemming material must confine gases for a sufficient duration to ensure complete and efficient detonation (Table 3).

Table 3. Recommended stemming materials for civilian explosives

Explosive Name	Manufacturer	Application Location	Detonation Velocity (m/s)	Brisance	Recommended Stemming Material	Reason
ANFO	Orica	Surface mines, quarries	2500-3000	Medium	Cement Mortar Sand, Clay	Low cost, good compressibility
Emulex 1	Dyno Nobel	Underground mines, quarries	5400	High	Cement Mortar	Excellent stability, water-resistant
Magnafrac	Austin Powder	Surface mines, quarries	5700	High	Cement Mortar, Water (Phials)	High performance, water resistance
Powergel	Orica	Underground mines, quarries	6000	High	Water (Phials), Cement Mortar	Gel explosive, requires water resistance
Pentolite	Ensign-Bickford	Demolitions, mines	7800	Very High	Cement Mortar, Clay	High sensitivity, requires stability
Tovex	DuPont	Underground mines, quarries	5500	High	Water (Phials), Clay	Good performance in wet conditions

Explosive Name	Manufacturer	Application Location	Detonation Velocity (m/s)	Brisance	Recommended Stemming Material	Reason
Ammonal	Dyno Nobel	Surface mines, quarries	3200-4500	Medium	Sand, Clay	Easy to prepare, low cost
Gelignite	Nitro Nobel	Underground mines, quarries	6000	High	Cement Mortar, Water (Phials)	Good performance in wet conditions
C4	Chemring	Military use, demolitions	8000	Very High	Cement Mortar, Clay	Stability and shock resistance
Slurry Explosives	Various Manufacturers	Surface mines, quarries	4000-5000	Medium-High	Sand, Clay	Good water resistance, medium sensitivity

Among the materials analysed, cement mortar provides the best confinement, followed by clay and sand.

5. Conclusions

The methodology for optimizing stemming materials involves a detailed evaluation of essential criteria to ensure maximum efficiency and safety of blasting operations.

By selecting appropriate stemming materials for each type of explosive and specific usage conditions, significant cost savings and performance improvements can be achieved in mining operations.

To improve the breaking yield of rocks fragmented through drilling and blasting operations, continuous investments in research and development are necessary to identify and implement new stemming technologies and materials. These efforts aim to enhance the quality of stemming, making it more efficient and environmentally friendly. Collaboration with academic and research institutions can accelerate progress in this field.

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